A Solar Backup System to Provide Reliable Energy in Presence of Unplanned Power Outages

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Abstract

Unreliable power grids in sub-Saharan countries have forced households to seek on-site power generation (self-generation) options. Although diesel generators have the largest share of backup systems, the use of solar systems has been growing. This paper presents a solar backup system including PV panels, a battery and a solar hot water (SHW) to provide both reliable energy and hot water to households. Moreover, two different configurations have been studied to improve the hot water system's performance. Whilst the SHW is limited to preheating the electric hot water in the first configuration, in the second it can individually provide the hot water for short-term uses in case of lack of energy. The solar backup system is equipped with an intelligent prediction-based controller that can control the power flow and the hot water temperature in the presence of power limitations and unplanned power outages. Evaluation of the proposed system using real datasets shows that, in addition to delivering reliable energy and hot water, the total cost of the solar solution over the project life is about 25% lower than the diesel generator's making it a more viable investment.

Keywords: Power Management Strategy, Prioritised Energy Resource Allocation, Diesel Generators, Optimal sizing, Solar Hot Water

1- Introduction

Sustainable energy supply in developing countries has a high impact on education, health, economic growth and poverty reduction (Blimpo and Malcolm, 2019). Many developing countries, especially in sub-Saharan Africa (SSA), experience electricity supply problems due to insufficient generation capacity, inadequate transmission and distribution infrastructure, and lack of investment in the power sector (Farquharson et al., 2018). According to the World Bank, only 47% of the SSA population has access to electricity, which is the lowest rate in the world (World Bank, 2021). Meanwhile, people who have access to electricity suffer from unplanned power outages and scheduled load-shedding (Kizilcec and Parikh, 2020). The low quality of the supplied power and frequent outages lead the households that need sustainable energy to seek self-generation options as a backup for the power grid (Baurzhan and Jenkins, 2017). Even though diesel backup generators are expensive to operate, contribute to global environmental emissions, and have a significant impact on local air quality, SSA has seen a significant increase in the use of such generators (Babajide and Brito, 2021; Marais and Wiedinmyer, 2016).

As Africa receives a large amount of solar radiation throughout the year (Pillot et al., 2019), the usage of photovoltaic-based systems has been investigated as an alternative to those diesel generators. Szabo et al. (2021) reported that photovoltaic (PV) mini-grids are cheaper than diesel generators in most SSA countries. This conclusion was further supported by Babajide and Brito (2021) who studied the replacement of diesel generators by PV-battery systems in Nigeria. Their study revealed that the solar PV option offers a cost savings of 60-65% over its lifetime compared to the traditional use of diesel generators for backup power generation. Focusing on dealing with unplanned power outages, Quansah et al. (2016) showed that grid-connected solar systems with battery storage can deliver proper and efficient operation. Indeed, in a study targeting residential customers in Libya where power outages are frequent, Amra et. al, (2019) showed that such a solution not only increased energy reliability but also was affordable and reduced household electricity bills.

All those studies suggest that PV/Battery systems are an effective solution to improve the energy reliability of customers who are connected to weak utility grids in SSA. However, it is also important to consider the impact of hot water systems: recent studies have reported that the consumption of electric heat waters accounts for up to 40% of total household electricity consumption (Hohne et al., 2019). This warrants the usage of solar hot water (SHW) systems alongside PV ones. Indeed, SHW can be used as either a preheater to increase the inlet water temperature of a hot water system or for low-consumption households as an independent hot water supply (Wazed et al., 2018).

This paper presents two solar energy solutions including PV panels, batteries, and a SHW which were designed to provide reliable energy and hot water for customers and support the utility grid by decreasing the electricity demand. While SHW operates as a preheater in the first configuration, in the second, it is equipped with an immersion heater to supply hot water individually in case of energy shortage. In both systems, a prediction-based power management strategy (PMS) autonomously controls the power flow and the hot water temperature. As those solutions were designed for middle-income and high-income households in developing countries, two representative case studies from Botswana have been selected to evaluate their performance. In addition, the effect of using such systems is investigated on the utility grid. This study revealed that not only can the proposed solutions increase the reliability of the delivered energy for individual households, but also, they can significantly reduce the total electricity demand. The main contributions of this paper can be summarized as follows:

- Design and development of an intelligent solar back-up system, including two different configurations for a domestic solar hot water, compatible with weak and stressed utility grids
- Data collection and preparation of two case studies representative of the target households
- Investigation of the aggregation effects of the proposed solution on the utility grid

The paper is organized as follows. Section 2 outlines the proposed solutions. Next, the proposed power management strategy for controlling the system is presented. This is then followed by the description of the approach used for optimal sizing of the system's components. Section 3 presents the two case studies in detail. In Section 4, energy performance, financial analysis, and comparison with alternative energy systems suitable for individual households are reported. Then, the effect of the proposed solutions on the utility grid is investigated. Finally, section 5 concludes the paper.

2- Methodology

Utility grids in SSA face problems such as power limitation during peak hours and unplanned outages. Consequently, customers need to rely on self-generation options to ensure reliable energy (Farquharson et al., 2018). First, this section presents a domestic and cost-effective solar solution for such customers. Then, the design of an optimal methodology for the system is described: it includes the development of an intelligent power management strategy and the calculation of the optimal size of its components. The PMS is designed in such a way that it provides reliable energy to customers even when faced with unplanned power outages and peak hour limitations. The optimal size should be calculated so that in addition to increasing the quality of the energy delivered, system costs are kept to a minimum.

2.1- Configuration of the Domestic Solar Solutions

The proposed domestic solar solutions consist of PV panels, batteries and a SHW which are controlled by an autonomous PMS. It is designed to provide reliable energy and hot water for customers who are connected to weak and unstable power grids. In terms of SHW, Integrated Collector Storage Solar Water Heaters (ICSSWH) are the most suitable technology as they provide insulated thermal storage and can store excess energy as heating that can be consumed when needed (Smyth et al., 2006). Moreover, they can be equipped with an immersion heater for the purpose of increasing hot water temperature in standalone mode. Based on this technology, the following configurations are proposed:

a) Basic: in this case, as shown in Fig.1 (a), the SHW preheats the water used by the electric hot water (EHW). The EHW can then bring the water to the appropriate temperature using its immersion heater.

b) Hybrid: In this case, in normal conditions, i.e., when either the utility grid is available or sufficient energy is supplied by the PV and the battery, the SHW is used as a preheater of the water heating system. However, when there is not enough electricity to provide the required energy to the electric hot water (EHW), the hot water is temporarily supplied from the SHW. In this case, the water inlet of the EHW is closed and the water outlet of the SHW is delivered directly to the consumer. The SHW is equipped with an immersion heater that can increase the temperature of the delivered hot water. As the SHW’s tank has a smaller volume than the ESW’s, it can provide hot water at the desired temperature with less received energy. This enables the system to supply hot water for short-term use as this may be necessary during times of energy shortage. The configuration of this case is illustrated in Fig.1 (b). Also, the summarized specifications of each configuration are shown in Table 1.

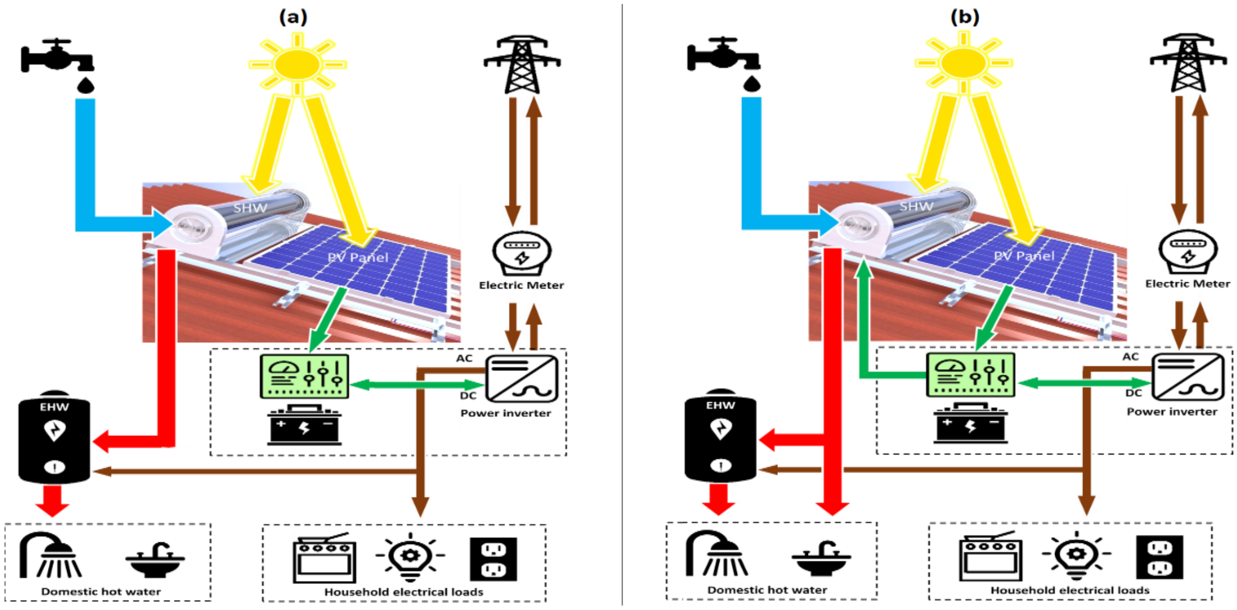

Fig. 1 Configuration of the domestic solar system: a) Preheating, and b) Preheating/Standalone solutions (The additional green arrow between the battery and the SHW represents the electrical connection of the immersion heater, and the split red arrow illustrates that the SHW can operate either in preheat mode or by supplying hot water individually) (SwanaSmartStore, 2021)

Table 1: Summarized specifications of each hot water system configuration

Configuration	**Functions of the solar hot water system**	**Integration of an immersion heater in the solar hot water system**	**Control of the hot water temperature**
Basic (Preheating)	Preheating the inlet water of the EHW	No	On/off controller of the EHW
Hybrid (Preheating/ Standalone)	- Preheating the inlet water of the EHW (Preheating) - Supplying hot water during times of energy shortage (Standalone)	Yes	- Switching between the operational modes of the hot water system - On/off control of the EHW (Preheating) - On/off control of the immersion heater of the SHW (Standalone)

2.2- Power management strategy

Since the proposed solutions are designed to provide both reliable electricity and hot water to customers, they require an integrated PMS to manage power flow and hot water temperature. Regarding power flow control, prediction-based methods have proved particularly efficient to optimise renewable energy systems (Ali et al., 2021). As they use Machine Learning models to predict power generation and consumption in the coming hours, controllers can use those estimates to optimally manage battery charge/discharge to handle future power shortage/surplus (Wang et al., 2019). Regarding battery management, various approaches can be considered including usage of evolutionary algorithms (Rajanna and Saini, 2016; Sepehrzad et al., 2020) or optimal rules (Kato et al. 2014; Marahatta et al., 2021).

Here, since the system is designed as an energy backup, during the normal mode of operation, the battery can only be charged. The stored energy in the battery is consumed to supply the electrical loads based on their priorities during the power outage or power limitation hours. Therefore, the first step in designing the PMS is to categorise the electrical loads and specify their priority (Alahmed and Al-Muhaini, 2020). Although prioritization could be specified according to a customer's specific requirements, residential loads would usually fit within the following categories:

- First priority: 'Normal Load' from, e.g., lighting, TV, electric oven, and refrigerator
- Second priority: 'Electric Heater Load'
- Third priority: 'Hot Water System Load' from both the SHW and the EHW
- No priority: 'Schedulable Load' from, e.g., washing machine, the usage of which can be scheduled, and air conditioner, which is only activated when the grid is available

In order to control these loads, a three-mode prioritized-based PMS is developed, offering normal, power limitation, and off-grid modes. When the utility grid is available, the first and second modes control the system, where they deal with off-peak and peak hours, respectively. However, in the case of brownouts, the third mode is activated. Fig. 2 illustrates the design concept of the PMS.

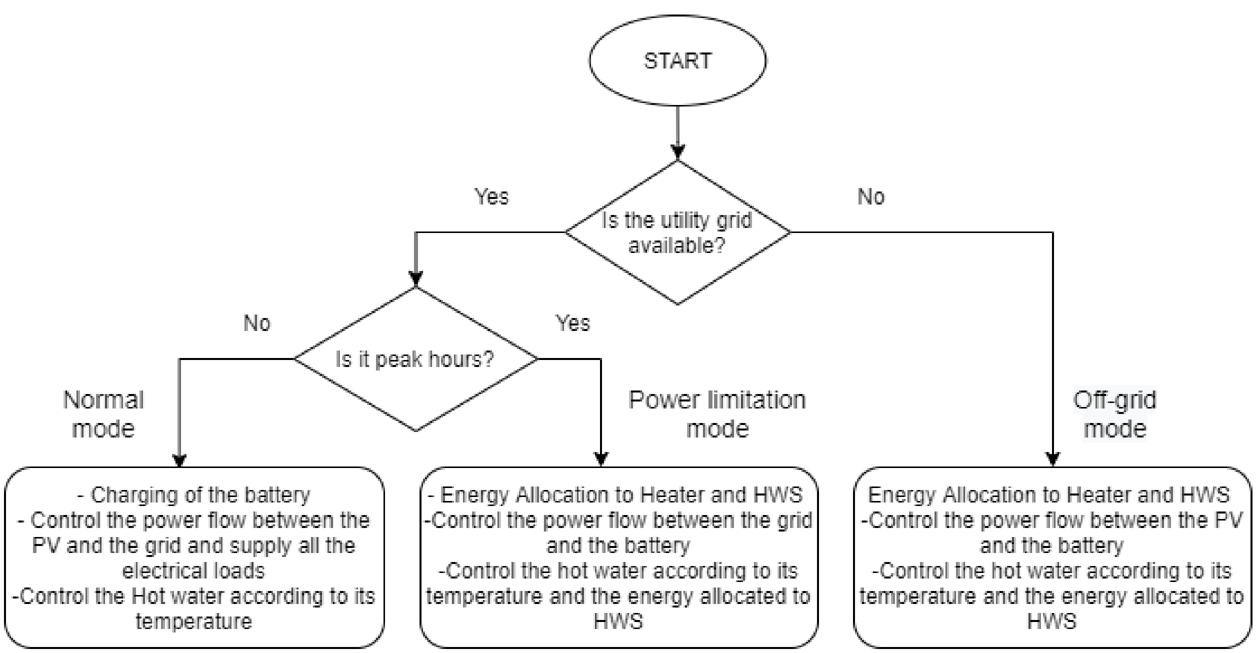

Fig. 2 The design concept of the PMS

As shown in Fig. 2, in the normal mode, the battery is fully charged by the output power of the PV or the utility grid. Any remaining generated PV power is first used to supply the electrical loads and, if there is any surplus energy, it is delivered to the hot water system where it is stored as thermal energy. In the second mode, i.e., during the peak load hours, as there is a limitation in terms of the maximum power that can be drawn from the utility grid, the battery must be managed in such a way that it can supply any load not fulfilled by the grid. Note that based on the set priorities, the battery only delivers the normal load and those associated with the electric heater and the hot water system. The algorithm relies on prediction values of normal load and electric heater load during the peak load hours. Finally, the PMS operates in its third mode (off-grid mode) when a brownout occurs, i.e., when the utility grid is unavailable. In such a case, the normal, the electric heater and the hot water system loads are supplied by PV output power and the energy stored in the battery. The PMS in this mode relies on prediction values of normal load, electric heater demand and PV power output for an N-hour period of power outage, where N is determined based on information specific to the utility grid. Fig. 3 shows a flow chart of the allocated energy calculations for each load type in the power limitation and off-grid modes.

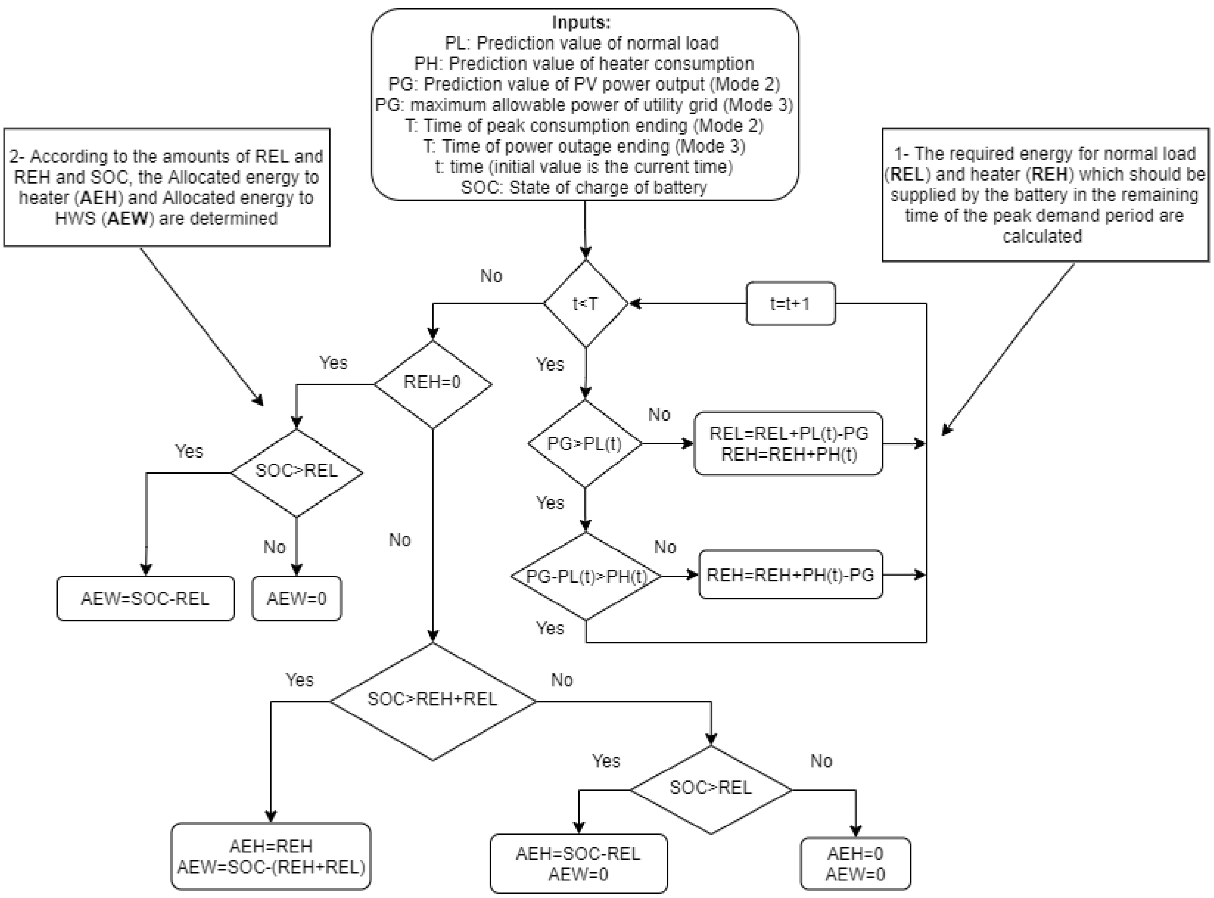

Fig. 3 Allocated energy calculations for each load type in the power limitation and off-grid modes

Once the amounts of energy allocated to the heater (AEH) and hot water system (AEW) are determined for the next time cycle, the integrated controller continuously monitors their power consumption and the hot water temperature. The flowchart of the integrated controller for each configuration, i.e., basic and hybrid, is presented in Fig. 4. The controller manages the loads based on their priorities. Initially, the loads are supplied by the PV power output or the grid. However, in the case of power shortage, the energy stored in the battery will be used. Before doing so, each electrical load that has consumed its allocated energy is turned off.

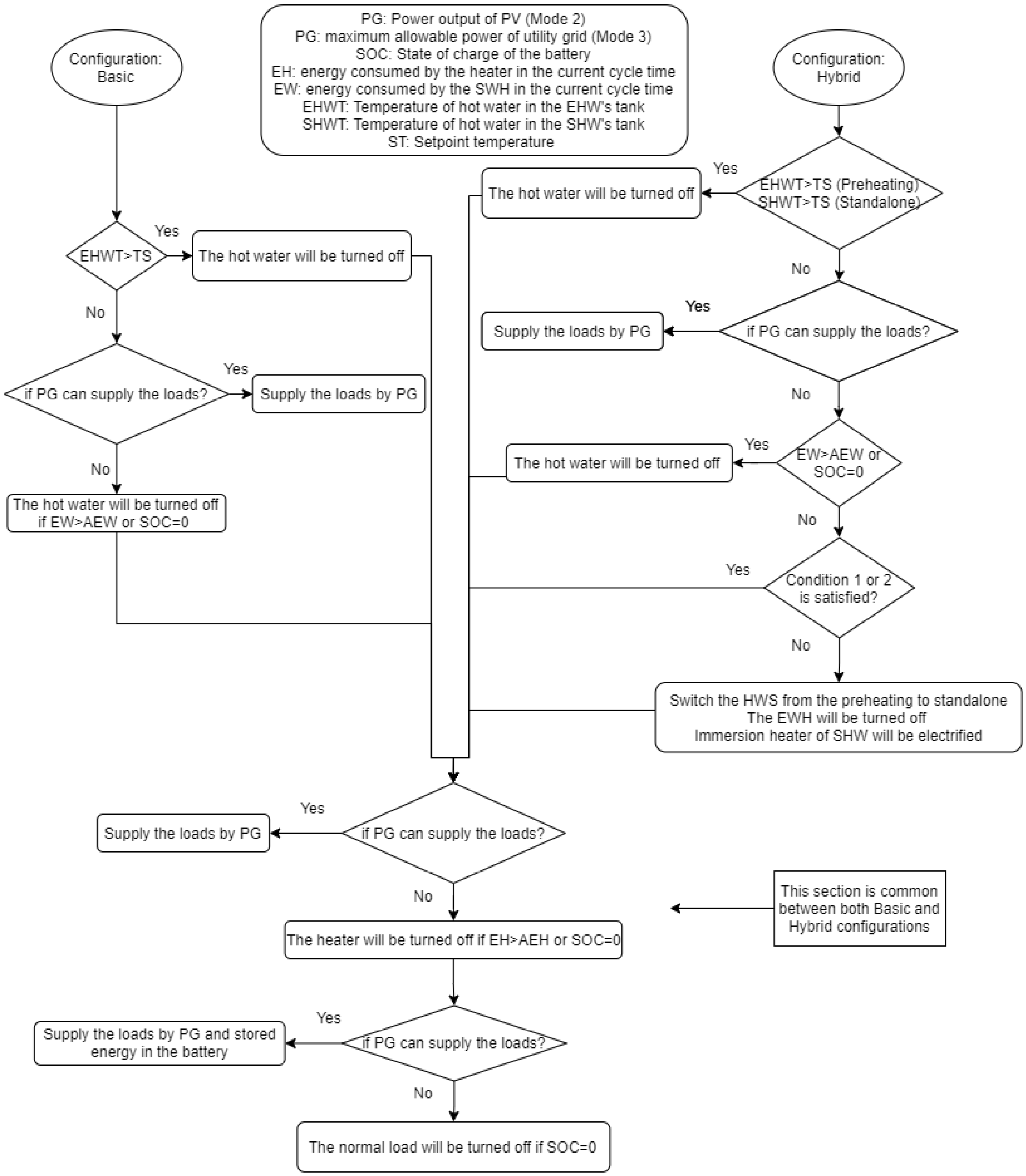

Fig. 4 Integrated controller for continuous control of the power flow and the hot water temperature (basic and hybrid configurations)

As shown in Fig. 4, the main difference between the two configurations is the way that the hot water is controlled. In the basic configuration, the hot water temperature in the EHW tank is compared to the setpoint temperature: if the hot water temperature is higher than the setpoint, the EHW heater is turned off; otherwise, it is controlled according to the amount of available energy. In the hybrid configuration, in addition to comparing and controlling the temperature, the operating mode of the HWS must be determined. If one of the following two conditions is satisfied, the system will operate in preheating mode, otherwise, it will switch to standalone.

Condition 1: if the AEW is delivered to the EHW heater, then EHWT≥ST

Condition 2: EHWT≥SHWT   if both EHW's and SHW's heaters have received the AEW

where EHWT and SHWT represent the temperatures of hot water in the EHW's and SHW's tanks, respectively. The first condition states that if the amount of energy allocated to the hot water system is delivered to the EHW's heater, the temperature of the hot water in the EHW's tank (EHWT) will meet the setpoint temperature (ST). If condition 1 is not satisfied, the controller will test condition 2. It checks that if the AEW is delivered to the immersion heater of the SHW, it can provide hot water with a higher temperature than the ESW.

2.3- Optimal Sizing

The PMS is most efficient if the components of the system, i.e., PV, battery and SHW are optimally sized, as this not only increases system reliability but also reduces the total cost of the system (Salehi Borujeni et al., 2017). To calculate the optimal size of components, a cost function must include capital cost (CC), operation and maintenance cost (OMC), replacement cost (RC) and annual electricity bill or grid cost (GC). As it is common practice, the annual operation and maintenance costs are estimated as a percentage of the capital cost (p). It is assumed that the replacement cost is equal to the original capital cost, while the replacement frequency is determined by the lifetime of each component. Moreover, to calculate the total cost, the present values of OMC, RC and GC are considered in the cost function (F) which is expressed by Eq. (1):

$$F = \frac{1}{crf}.GC + \sum_{i=1}^{m} CC_i + OMC_i + RC_i = \frac{1}{crf}.GC + \sum_{i=1}^{m} CC_i\left(1 + \frac{p_i}{CRF} + k_i\right) \quad (1)$$

Where *i* represent the i^th components, *m* the number of components, CRF is the capital recovery factor and k_i is the present value factor of the i^th components. These parameters are calculated using the following equations:

$$CRF = \frac{ir(1+ir)^R}{(1+ir)^R - 1} \quad (2)$$

$$k_i = \sum_{n=1}^{\left\lceil \frac{R}{L_i} \right\rceil} \frac{1}{(1+ir)^{L_i \times n}} \quad (3)$$

where R is the system lifetime, L_i is the lifetimes of the i^th components and ir is the discount rate. The objective functions are optimized subject to reliability and hot water temperature constraints.

- Reliability constraint:

The Equivalent Loss Factor (ELF) index is considered as the reliability constraint for both normal load ($l = 1$) and heater load ($l = 2$) as follows (Mohseni et al., 2019):

$$ELF_l = \frac{1}{H}\sum_{t=1}^{H}\frac{UL_l(t)}{TL(t)} < e_l\,, \qquad l = 1, 2 \tag{4}$$

Where H describes the number of hours, e is the ELF criteria, and $TL(t)$ and $UL(t)$ represent the total amount of electrical load and unmet load at the t^{th} hour, respectively.

- Hot water temperature constraint:

The hot water temperature (HWT) constraint expresses the percentage of hot water which is delivered to the household at a lower temperature than the desired temperature (i.e., unmet hot water). It is estimated by Eq. (5):

$$\mathrm{HWT} = 100 * \sum_{t=1}^{H}\frac{UHW(t)}{THW(t)} < e_t, \tag{5}$$

where $THW(t)$ and $UHW(t)$ denote the total hot water consumption and the amount of unmet hot water at the t^{th} hour.

3- Case Studies

The evaluation of the proposed solution was conducted using two case studies involving a middle-income or a high-income household. They are considered to access the electrical supply at tier 4 and tier 5 levels, respectively. Tier 4 houses use essential and high-power appliances whose annual consumption is more than 1250 kWh and whose daily energy capacity is higher than 3.4 kWh. Tier 5 houses on the other hand have very high-power appliances in addition to using Tier 4 appliances. The annual consumption for this level is more than 3000 kWh and the daily energy capacity is higher than 8.2 kWh. Households in both levels have space heating systems, but an air conditioning system for cooling (a very high-power appliance) is only considered for high-income households (Bhatia and Angelou, 2015). Since data collection and preparation is a major part of system development, it is discussed before providing details about the two case studies.

3.1. Data Collection and Preparation

Historical data of power consumption and power production of the energy resources are required for the optimal design of a solar system. A general recommendation is to use a one-year set of measured data that includes seasonal behaviour and different patterns (Bigdeli et al. 2017; Blodgett et al. 2017) so that the results derived from the optimization method are closer to their actual optimal values. However, since measuring data is not cost-effective for small solar systems, an alternative approach is to use a mixture of real and synthesized data to produce the required datasets. The methodology used to prepare the datasets required for this study is presented below.

3.1.1- Power generation of PV

One alternative for a measured dataset of PV power output is to use either the reanalysis or satellite-driven databases. Well-known open-source databases such as SARAH, MERRA-2 and ERA5 provide solar radiation data to users and designers with different resolutions. Such data are available at many locations around the world for long periods of time (Boilley and Wald, 2015). Evaluation of the accuracy of these datasets has shown that they are reliable and suitable to design solar systems (Yang and Bright, 2020). Here, the Photovoltaic Geographical Information System (PVGIS) is used as it offers an online tool with various databases providing solar radiation and ambient temperature with hourly resolution

3.1.2- Power Consumption

As there are many variables, such as the number of people in a household, the demographics, the size of the house, the income level, and the number of electrical appliances, affect a household's consumption of power, it is challenging to find a way to amalgamate synthesized data consistent with real data. In order to tackle this problem, it is proposed to, initially, classify the households' power consumption. Indeed, as mentioned in section 2.1, a residential electrical load can be divided into the following major categories:

a) Cooling/Heating: The highest residential electricity consumption is associated with heating and cooling systems. Moreover, this type of load is responsible for the main seasonal behaviour of the total power consumption, which is highly correlated with ambient air temperature (T_a) (Palacios-Garcia et al., 2018). As this relationship is highly liner (Kamel et al., 2020; Manivannan et al., 2017), a linear model is used based on the rated power (P_R) of the cooling/heating systems and hourly ambient temperature to estimate the power consumption ($L(t)$) of those systems:

$$L_C(t) = \begin{cases} 0 & T_a(t) > T_{max,C} \\ (P_{R,C} - P_{M,C})\left(\frac{T_a(t)-T_{min,C}}{T_{max,C}-T_{min,C}}\right) + P_{M,C} & T_{min,C} \geq T_a(t) \geq T_{max,C} \\ P_{N,C} & T_a(t) < T_{min,C} \end{cases} \quad (6)$$

$$L_H(t) = \begin{cases} P_{N,H} & T_a(t) > T_{max,H} \\ (P_{R,H} - P_{M,H}).\left(\frac{T_a(t)-T_{min,H}}{T_{max,H}-T_{min,H}}\right) + P_{M,H} & T_{min,H} \geq T_a(t) \geq T_{max,H} \\ 0 & T_a(t) < T_{min,H} \end{cases} \quad (7)$$

Where C, H are the indices associated with the cooling and the heating systems, respectively. P_M is the minimum input power of the system that is provided by the manufacturer. T_{min} and T_{max} are specified at the design stage by the user based on the temperature setpoints.

b) Hot water system: The electric HWS is one of the largest sources of electricity demand. Its power consumption is directly related to the hot water demand, ambient temperature and system specifications such as the tank capacity, the rated power of the immersion heater and the heat loss coefficient (Booysen et al. 2019). In the proposed solution, the HWS consists of the SHW and the EHW whose mathematical models are used to calculate their power consumption are presented in section 3.2.

c) Normal loads: Although the remaining electrical load has a more regular and sometimes periodic pattern, different load profiles should be considered for weekdays and weekends (Anderson et al., 2013). Thus, in this study, the design of the solar backup system relied on normal load data that were collected hourly for a week.

d) Schedulable load: This load has a small share of the total consumption and since its usage time is flexible, households can shift the consumption to the off-peak hours. This load is simulated through a uniform distribution function applied during the usual usage hours of the household during off-peak times.

3.2- Mathematical models of components

In order to simulate the system and evaluate the proposed solution, the system components must be modelled. Here, in addition to the mathematical models associated with the proposed solutions' components, the diesel generator model is also presented as a potential alternative to the solar systems.

3.2.1- Photovoltaic Panel

The output power of a PV panel, p_{PV}, mainly depends on the solar irradiation and the solar cell temperature. The following equation, recommended by Maleki and Pourfayaz (2015), is used to determine its output power:

$$p_{PV}(t) = P_{R,PV} \times \frac{I(t)}{I_{ref}} \times [100 + N_T\left(T_c(t) - T_{ref}\right)/100], \quad (8)$$

where $I(t)$ describes the total solar radiation reaching the PV panel surface (W/m^2) at time tth, I_{ref} is the solar radiation at a reference condition (conventionally 1000 W/m^2), $P_{R,PV}$ is the PV rated power, T_{ref} is the cell temperature at a reference condition (conventionally set at 25 ˚C), N_T is the temperature coefficient of the photovoltaic panel (%/°C). Finally, the cell temperature, $T_c(t)$, is calculated by Eq. (9):

$$T_c(t) = T_a(t) + I\left(\frac{NOCT-20}{800}\right), \quad (9)$$

where $T_a(t)$ is the ambient air temperature and $NOCT$ is the Normal Operating Cell Temperature when the PV module is operating under an 800 W/m^2 irradiance and a 20 ˚C air temperature. Note that $NOCT$ is among the PV module specifications provided by the manufacturer.

In addition, as reduction of output power is an issue for PV systems, 16% of power loss, which includes losses of cable, dust, reflection, and inverter, is considered for the delivered power (Ekici and Kopru, 2017). As one of the other causes in increasing the solar system losses is the amount of Total

Harmonics Distortion (THD) (Alhafadhi and Teh, 2019), it is assumed that use of adaptive filters reduced such losses (Alhafadhi et al. 2020).

3.2.2- Battery

The charging and discharging processes of the battery can be described by the following equations (Mohammadi and Mohammadi, 2014):

$$E_{batt}(\mathrm{t}+1)=\begin{cases} min\left\{\left(E_{batt}(t)+\Delta t.\frac{P_{batt}(t)}{\eta_c}\right),\ \ E_{batt,max}\right\} & battery\ charge \\ \max\left\{\left(E_{batt}(\mathrm{t})-\Delta \mathrm{t}.\frac{P_{batt}(\mathrm{t})}{\eta_d}\right),\ \ E_{batt,min}\right\} & battery\ discharge \end{cases} \tag{10}$$

where:

$$P_{batt,min}\leq P_{batt}(t)\leq P_{batt,max}, \tag{11}$$

$E_{batt}(t)$ denotes the energy in the battery at time t, η_d and η_c stand for the battery discharge and charge efficiency, $E_{batt,min}$ and $E_{batt,max}$ represent the minimum and maximum amount of allowed energy in the battery, $P_{batt}(t)$ expresses the power supplied to or discharged from the battery at time t^{th}, $P_{batt,min}$ and $P_{batt,max}$ describe the minimum and maximum amount of allowed power supplied to or discharged from the battery.
This study uses the Absorbent Glass Mat (AGM) which is an advanced lead-acid battery. The depth of discharge (DoD) is considered to be 50% according to the manufacturer recommendation.

3.2.3- Hot water system

The temperature of hot water in the SHW's tank is calculated by the following equation (Pugsley et al., 2020):

$$T_w(t+1)=T_w(t)+\frac{Q_H\,(t)+X\cdot Q_f\,(t)+(1-X)\,Q_r\,(t)-Q_D\,(t)}{mc_p}, \tag{12}$$

where T_w is the hot water temperature (˚C), Q_H, Q_f, Q_r and Q_D represent, respectively, the energy of the immersion heater, the forward mode solar gain energy, the reverse mode energy loss and the energy delivered by the system at time t. If $Q_f(t)>Q_r(t)$ then the thermal diode is in the forward operating mode and $X=1$, otherwise, it is in the reverse operating mode and $X=0$. The forward mode solar gain energy is defined as:

$$Q_f(t)=A.\mathit{\Delta t}(K\cdot G\ F\tau\alpha-FU_L[T_w(t)-T_a(t)])\left[e^{\frac{A.FU_L\mathit{\Delta t}}{m\cdot c_p}}\right]^{-1}, \tag{13}$$

where A is the planar area of the absorber exposed to direct sunlight (m^2), $\mathit{\Delta t}$ is the time period (s), G is the solar radiation ($W.m^{-2}$), $F\tau\alpha$ is the optical coefficient, FU_L is the thermal loss coefficient during the forward mode operation ($W.m^{-2}C^{-1}$), T_a is the ambient air temperature (˚C), m is the mass of water in the storage tank (kg), and c_p is the specific heat capacity at constant pressure (J.kg^{-1}C^{-1}). Finally, K is a solar incidence angle parameter dependent upon the time of day (where h is the difference of the current time to solar noon) and the orientation of the hot water system. For a SHW whose axis is oriented east-west, the parameter K can be approximated by:

$$K = \begin{cases} 1, & -2 < h < 2 \\ \sqrt{\frac{2.5}{|h|}}, & \text{at other times} \end{cases} . \quad (14)$$

The reverse mode energy loss is:

$$Q_r(t) = -Q_w(t)\left(1 - \left[e^{\frac{A.U_r \Delta t}{m \cdot c_p}}\right]^{-1}\right), \quad (15)$$

where U_r is the thermal loss coefficient during the reverse mode operation (W.m^{-2}C^{-1}), and Q_w is the thermal energy contained in the stored hot water. It is calculated as follows:

$$Q_w(t) = mc_p[T_w(t) - T_a(t)]. \quad (16)$$

If hot water is extracted from the system, $Q_D(t)$ represents the heat energy delivered by the system at time t.

$$Q_D(t) = M(t) \, . \, c_p[T_w(t) - T_{in}(t)], \quad (17)$$

where M represents the mass of water draw-offs (kg) and T_{in} is the temperature of incoming water at the inlet of the hot water system (°C). Eq (12) is also used to calculate the hot water temperature in the EHW's tank, but, in this case, Q_f is equal to zero.

3.2.4- Diesel Generator

The relationship between the amounts of fuel and the output power of the diesel generator can be modelled as a linear relationship with the diesel generator rated power estimated as follows:

$$F = 0.33P_{dg} + 0.05, \quad (18)$$

where P_{dg} is the output power of the diesel generator in terms of kWh and F represents the amount of fuel consumption in litres (Habib Ullah, 2013).

3.3- High-income household

The high-income scenario considers a house located in Francistown, Botswana, which was occupied by a high-income 4-person household. The normal load from this house was measured for a period of one week from 04/10/2020 to 11/10/2020. The average daily normal load is 9886 (Wh/Day) with a minimum and a maximum of 8406 (Wh/Day) and 10701 (Wh/Day), respectively. As hourly hot water consumption was not collected, it was estimated based on actual water bills, interviews with households, and relevant consumption datasets available with hourly resolution provided by Booysen et al. (the open-source datasets are available in http://bit.ly/EWHSavingsESDDataset). Indeed, they offer 77 hot water consumption datasets for different households in South Africa with hourly resolution (Booysen et al. 2019; Roux et al. 2018). Thus, the average hot water consumption for the house is considered to be 108.6 L/Day, while the minimum and the maxima are 27.5 L/Day and 287.5 L/Day, respectively. The hourly profiles of the electricity and hot water consumptions are represented in Fig. 5. Table 2 summarizes additional information regarding the house's existing appliances.

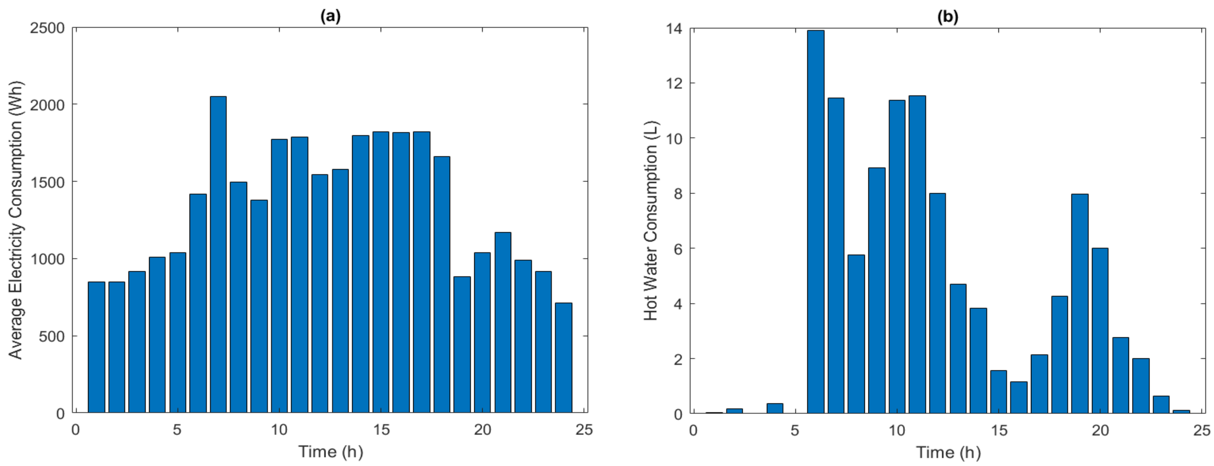

Fig. 5 Hourly profiles of a) the electricity load, and b) the hot water consumption

Table 2: Additional information regarding the high-income house

Item	Description
Cooling system	Three 9000-BTU (2500W) air conditioners with a coincidence factor of 0.66
Heating system	Three 1500W electric heaters with a coincidence factor of 0.66
EHW system	The capacity of 107L with a 3000W immersion heater
Maximum of the total load	10114 Wh

3.4- Medium-income household

The medium-income scenario considers a house located in Harare, Zimbabwe, which was occupied by a medium-income 4-person household. The normal load from this house was measured for a period of one week from 29/11/2020 to 06/12/2020. The average hourly of the normal load is 9087 (Wh) with a minimum and a maximum of 7782 (Wh) and 10473 (Wh), respectively. For this house, same as the high-income house, a relevant hot water consumption dataset available with hourly resolution provided by Booysen et. al is considered (http://bit.ly/EWHSavingsESDDataset). The average consumption is 63.5 L/Day and the minimum and maximum are 0 L/Day and 158 L/Day, respectively. The hourly profiles of normal load and hot water are represented in Fig. 6. Table 3 summarizes additional information of the house derived from audit results.

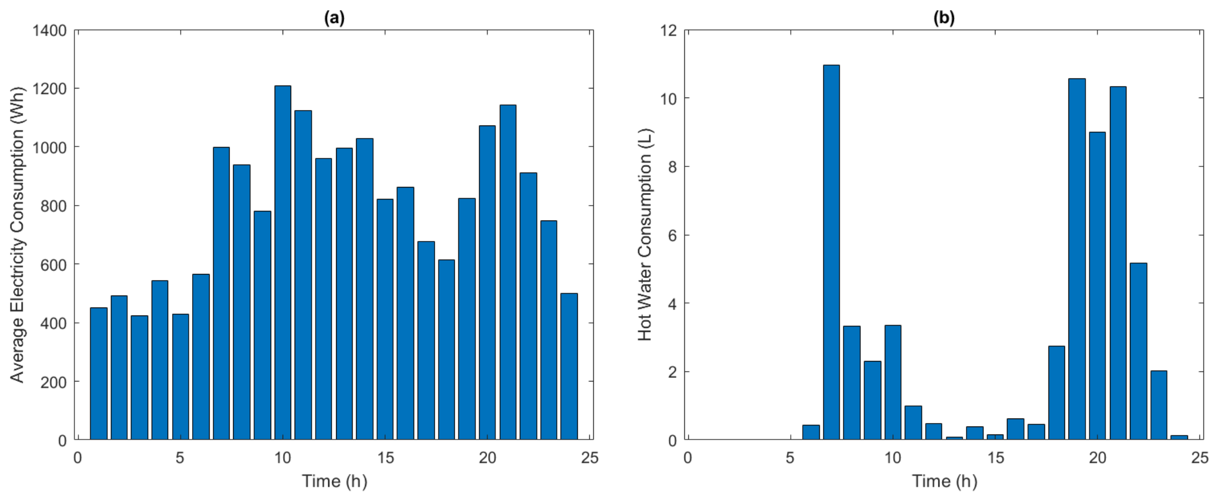

Fig. 6 Hourly profiles of a) the electricity load b) the hot water consumption

Table 3: Additional information of the medium-income house

Item	Description
Cooling system	N/A
Heating system	Two 1000W electric heaters with a coincidence factor of 0.5
EHW system	The capacity of 100L with a 3000W immersion heater
Maximum of the total load	4258 Wh

4- Results and discussion

The results of the design and simulation of the proposed solar system along with its financial analysis are discussed in this section. Although one of the measured datasets is related to a house which is located in neighbouring Zimbabwe, in order to make comparisons more meaningful, both households have been considered to be located in the same location in Botswana. The costs and specifications of the individual components as well as the fuel cost of the diesel generator in the local market in Botswana are presented in Table 4. These costs, expressed in US dollars, were valid in June 2021. In addition, Botswana electricity tariff from the Botswana Power Corporation (BPC) is considered to calculate households' electricity bills (BPC, 2021).

Table 4: Costs and specifications of the solar solution's components and fuel cost

Component	Initial cost	Cost of maintenance (Annual)	Lifetime (Years)	Smallest unit
PV	1 $/W	2% of initial cost	25	280 W
SHW	600 $	2% of initial cost	25	28 L
Immersion heater and valves	100 $	-	25	-
Battery	0.25 $/Wh	-	8	120 Wh
Inverter	0.4 $/W	-	15	-
Battery charge controller	0.4 $/W	-	15	-
Diesel generator and control panel	220 $/kW	5% of initial cost	15000 (hours)	500 W
Fuel cost	0.9 $/L	-	-	-

4.1- Optimization results

As mentioned earlier, due to power limitations and unplanned power outages, customers need to use energy backup systems. Therefore, in order to investigate the performance of the proposed solar system, three different systems are considered as follows:

Case 1: Considering that diesel generators are widely used in sub-Saharan countries, this system has been selected for comparison with the proposed solar solutions.

Case 2: Usage of the solar and storage solution where the basic configuration for the HWS is considered.

Case 3: Usage of the solar and storage solution where the hybrid configuration for the HWS is considered

The three cases were simulated using MATLAB software for both medium-income and high-income households. Regarding the diesel generator, its capacity was determined using the maximum household power consumption. Moreover, it is equipped with a control panel that automatically controls the system during a power outage or peak hours. For Cases 2 and 3, the cost function with its related constraints (see Section 2.3), is minimized by a genetic algorithm to determine the optimal sizes of the PV, the battery, and the SHW as well as the setpoint temperature of the HWS. Regarding the ELF indexes (Eq. (4)) for normal load and heater, as recommended in previous studies, the criteria were set at 0.0001 and 0.005, respectively (Mohseni, 2019). Moreover, the hot water temperature criteria in Eq. (5) was set at 40˚C to provide households with a desirable hot water temperature (Critchley and Phipps, 2007). Moreover, in this simulation, it is assumed that unplanned power outages occur randomly 4.5% of the time with an average duration of 5 hours per event, which is a common occurrence in the SSA (Enterprise Surveys, 2021).

As the proposed PMS is a prediction-based method, it is assumed that the prediction error of each variable, including output power of PV, power consumption of normal load, and heater, is 20%. Previous researches show that by using the novel machine learning approach, the variable can be accurately predicted. Raza et al. (2019) developed different models to predict the PV output power which the best model has an error of less than 10%. On the other hand, although the prediction error of individual households has been reported higher than 20%, i.e. Gajowniczek and Ząbkowski (2017) made a comparison between different methods with the lowest prediction error of 23%, it should be noted here the prediction of normal load and electric heater which are more periodic are needed, so it is fair to conclude that the considered error is a pessimistic assumption.

4.1.1- High-income household

The optimization results based on the provided information and collected data from the high-income house are summarized in Table (5).

Table 5: Optimization results for the high-income household

	PV (×280W)	**Battery (kWh)**	**SHW (×28L)**	**Setpoint (˚C)**	**Diesel generator (kW)**	**Total Cost $ (25 Years)**	**Initial cost of back-up system $**	**Electricity bill + Fuel cost (Annual)**	**Surplus Energy (kWh/year)**	**ELF**		**Percentage of unmet hot water**
										Normal Load	**Heater**	
Case 1	-	-	-	54	7.5	36779	1650	1655	-	0.00015	0.00002	0
Case 2	14	8.9	1	51	-	27670	9708	537	2227	0.00007	0.005	0.085
Case 3	14	8.9	1	51	-	27756	9808	536	2218	0.00007	0.005	0.009

As shown in Table (5), based on the household consumption, a 7.5 kW diesel generator is suitable for the high-income household. By adjusting the setpoint temperature of the hot water system to 54˚C (i.e., the minimum temperature which can satisfy the hot water constraint), this backup system can provide reliable energy and hot water to the household. While the total unmet load by the grid is close to 0.045 (as the power outage of the utility grid is 4.5%), it is reduced to less than 0.0002 by using this diesel generator. Note that the values reported in Table (5) are based on the assumption that the diesel generator does not fail within the required hours. In this case, only the ELF of the normal load exceeds the set criteria (i.e., 0.0001). One major reason for the popularity of this system is its low initial cost. However, in addition to the electricity bill, the cost of fuel must also be considered and increases the annual household cost, which, for this case study, reaches $1655.

Case 2 presents the simulation results of the first proposed solar solution, which includes the PV panels, the battery, and the SHW. The size of components, as well as the temperature setpoint, have been specified by the described optimization method. This system, which is controlled by an intelligent controller, provides the reliable energy and hot water required by the customer. Although previous studies have presented solutions for modeling the reliability of solar systems (Abunima and Teh, 2020), this would also require modeling the even lower reliability of the diesel generator, which would introduce additional assumptions. Thus, to make the comparison between the two systems as fair as possible, this study considers that both of them are always available during operation time. The proposed system has a significantly higher initial cost than the diesel generator, however, its total cost during the lifetime of the installation is 25% lower. Indeed, as the customer does not have to pay for fuel, the bill and fuel costs are reduced by 68% compared to those of the diesel generator. Here, the surplus energy generated by the PV panels, which is not needed to fulfil electricity or hot water demands, is exported to the grid at the basic tariff. This amount reduced the household's annual electricity bill by about $190.

The proposed solar system in case 3 differs slightly from case 2 in that it uses a hybrid configuration for the hot water system. In this configuration, the SHW can be used standalone to supply the required hot water in the case of energy shortage. The initial cost for this system is only $100 more than case 2, i.e., about an additional 1% of the total initial cost, as the purchase of an immersion heater and valves is needed. The main consequence of this additional investment is that the percentage of unmet hot water is reduced by almost a factor of 10 when compared with Case 2, which indicates a much better-quality hot water supply. Additional results, not shown, reveal that in 7.9% of the cases when the system operates during a power outage or peak hours, the hot water system switches from basic to standalone mode, leading the SHW to supply the hot water individually.

4.1.2- Medium-income household

The optimization results based on the provided information and collected data from a medium-income house are summarized in Table 6.

Table 6: optimization results of medium-income household

	PV (×280W)	**Battery (kWh)**	**SHVatcher (×28L)**	**Setpoint (˚C)**	**Diesel generator (kW)**	**Total Cost $ (25 Years)**	**Initial cost of back-up system $**	**Electricity bill + Fuel cost (Annual)**	**Surplus Energy (kWh/year)**	**ELF**		**Percentage of unmet hot water**
										Normal Load	**Heater**	
Case 1	-	-	-	48	5	23108	1200	1041	-	0.00015	0.00002	0
Case 2	8	8.3	1	47	-	17770	6600	283	873	0.00009	0.0048	0.066
Case 3	9	7.6	1	48	-	17470	7018	247	1152	0.0001	0.0046	0.0399

A 5-kW diesel generator is provided to cover the electrical demand of this household during a power outage. Similar to the high-income scenario, the diesel generator can provide sustainable electricity and hot water for the household. Although this system has an initial cost of $ 1,200, the total annual electricity bills and fuel costs are more than 4 times the solar system's, which makes the total cost of this system 30% higher than the solar system over 25 years.

Since the optimized solar system requires fewer panels and lower battery capacity than the high-income scenario, the initial cost of the solar solution for the medium-income household is 32% lower than this of the high-income household. Similarly, results demonstrate that the solar system can supply reliable hot water and energy to the household, even in the case of unplanned power outages. As with the previous scenario, surplus energy is exported to the grid at the basic tariff. These revenues for Case 2 and Case 3 are $84 and $98 respectively, which reduces the amount of annual bills.

Compared to Case 2, Case 3 with its hybrid configuration for the hot water system not only delivers a lower total cost but also provides better performance in terms of hot water provision. As Table 6 shows, the percentage of unmet hot water in case 3 decreased by 45% compared to case 2. Additional results, not shown, reveal that in 6.9% of the cases when the system operates during a power outage or peak hours, the hot water system switches from basic to standalone mode, leading the SHW to supply the hot water individually.

4.2. The solution effects on the utility grid

The proposed solar system reduces stress on the utility grid by not only reducing power consumption but also by providing it with surplus energy. This is illustrated in Fig. 7 where the average of energy demanded from the utility grid is compared with that of households that use a diesel generator as a backup system in both the medium- and high-income scenarios. One should note that the electricity demand of customers using the proposed solar solution is calculated by subtracting the exported energy from the imported energy.

Fig.7 reveals that the solar system in both case studies reduces the electricity demand significantly in particular from 6 to 21 which are the peak and the mid-peak power consumption hours. This results from both the production of solar panels during these hours and battery charging during off-peak hours. In the high-income house scenario, the average grid energy demand is reduced by 45% during a 24-hour period and 57% for the previously mentioned period. These reductions are even higher, i.e., 53% and 64% respectively, in the medium-income house.

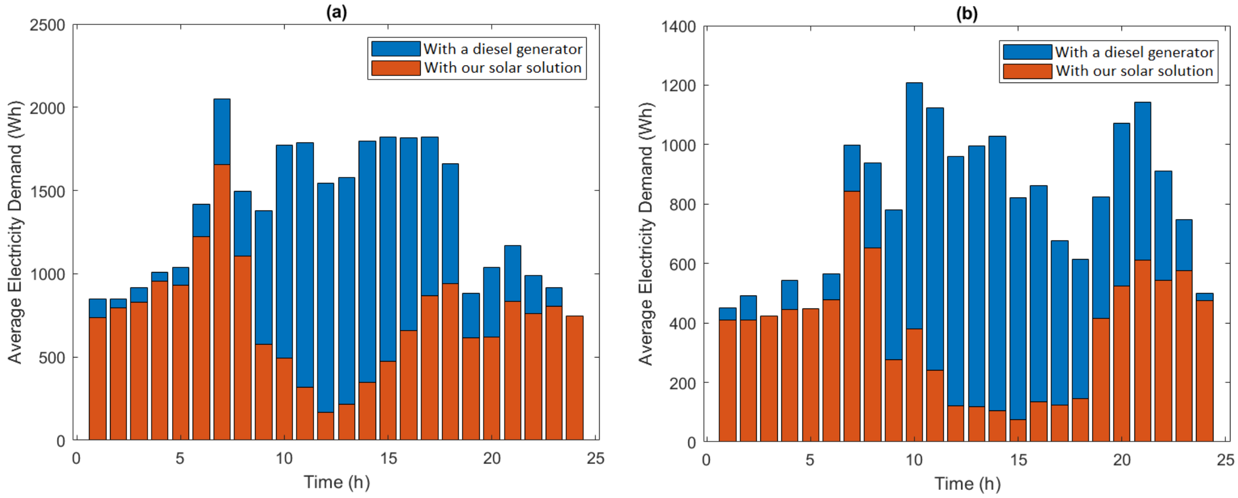

Fig.7. Average of energy demanded from the utility grid in case 1 and case 3 for a) high-income, and b) medium-income households

4.3- Discussion

Experiments conducted on two very different case studies, i.e., high- and medium-income households, suggest that a green, reliable, and cost-effective backup system can be delivered to a large variety of users by customizing the components of the proposed solar and storage solution according to their profile. Indeed, in all studied cases the proposed solution, not only meets stringent electricity reliability and hot water temperature constraints but also costs around 25% less during the lifetime of its installation when compared to popular diesel generators. One should also note that, among the two proposed configurations, whereas their total 25-year costs are similar, the hybrid one proves to deliver a significantly improved hot water service.

The main issue with the proposed solution is its initial cost which is around 6 times that of an equivalent diesel-based backup system. However, as this study shows, those solutions significantly reduce both power and peak consumption from the utility grid – especially during peak and mid-peak power consumption hours -, while providing it with surplus energy. As this contributes to tackling insufficient generation capacity and risks of unplanned power outages, it is expected that governments and/or utility companies will support the acquisition of such systems by households by offering them advantageous credit conditions. In such a scenario, high- and medium-income households would have a strong incentive in investing in a solar and storage solution instead of a diesel generator.

5- Conclusion

This paper presents an integrated electricity and hot water solar solution that can be used as a backup system for households that do not have access to a reliable utility grid. This system includes PV panels, a battery and a SHW whose hot water system is proposed in two configurations. In the first configuration, the SHW only operates as a preheater for the EHW, but in the second, it is equipped with an immersion heater, for supplying hot water individually in case of energy shortage. As part of the solution, an intelligent power management strategy is developed to manage the power flow in the system. The proposed PMS is a prediction-based method that can control the power flow and hot water temperature during the power limitation hours and in the unplanned power outage. The performance evaluation on two different case studies shows that although initially, the solar system costs more than a diesel generator, its total cost over 25 years is up to 30% lower than the diesel generator. Moreover, the solar system can provide sustainable support for weak and stressful power grids with a significant reduction of 45% to 64% in households' electricity demand. In addition, the consideration of other advantages such as ease of maintenance, no need for fuel supply, reduction of both air and noise pollution confirms that the proposed solar system is the best self-generation option in terms of backup for the power grid. The results also show that the hybrid configuration, in addition to a slight reduction in total cost, is able to provide hot water more reliably to households.

Acknowledgements

This work was supported by Innovate UK [grant number 133910] as part of the project SwanaSmartStore. The authors would like to thank Robert Hanna from African Sun Energy (ASE) and Empowered Ltd for the provision of the data collected for the two case studies. The authors will also like to thank the partners from the Centre for Sustainable Technologies (Ulster) and SolaFin2Go project funded by the Engineering and Physical Sciences Research Council (EP/R035954/1) and Innovate UK Energy Catalyst Round 5 (IUK/133219) for their contribution to the paper.

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